CyberRider

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DARPA Grand Challenge 2005

Technical Paper

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Abstract

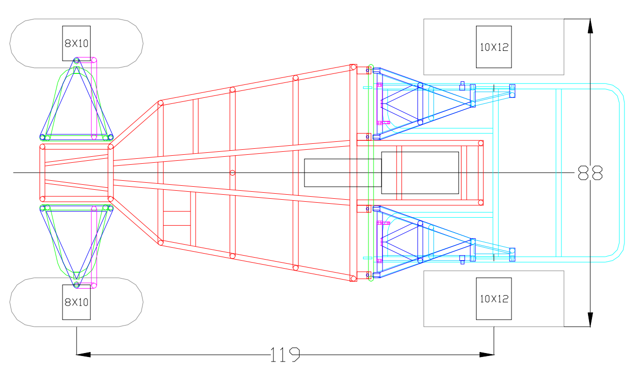
Team CyberRider was an original qualifier for the DARPA Grand Challenge 2004. The all-volunteer team has diligently enhanced their Baja Racing Dune Buggy to compete in the DARPA Grand Challenge 2005. The team's approach to solving autonomous control is to create an environment that assesses the environment around the vehicle and manage a decision system that weighs a confidence value from all sensors to determine the best path to follow. Implementing the assimilation of environment technique allows the robot to adapt quickly to any environment it is asked to navigate.

The all-volunteer team of CyberRider was brought together in the interest of science and the promotion of robotic studies. In addition to the development of the vehicle the team has also made a conscious choice to education interested local high schools in the Grand Challenge and the study of robotics. A contest was held by local high schools for building a solar tracking device. High School students with their teacher were able to learn how to develop and implement a working device.

Team CyberRider is not your typical hobby shop team of volunteers. The team is composed of accomplished engineers in their field of study. That expertise is what they each bring to the project. The team runs the project as a professional business with project plans, test plans, safety plans, and a business plan on what is required to win the race. Without the contributions of all team members collectively then our success would not have been possible.

1. Vehicle Description

1.1. Introduction



A robust custom built vehicle with long travel air suspension generates a smooth ride and enables traversing rough terrain at high speeds. Large tires and high ground clearance allows the environmental sensors to disregard smaller obstacles.

1.2. Vehicle Details

Custom tubular chassis Dune Buggy.
Maximum physical dimensions: length 210" (bumper to bumper), wheelbase 119", Track Width Front 85", Rear 88", height (neutral suspension) 72".
Propulsion is achieved by a Propane powered six cylinder internal combustion engine (GM V6 3.1L). A 3 speed automatic transaxle outputs to a unique drive line consisting of 2 drive shafts, each having 2 constant velocity (CV) joints. Each drive shaft is connected to a drive sprocket on a bearing supported shaft, anchored to the frame, which is in line (concentric) with the pivot of the rear trailing arm. A driven sprocket is bolted to the hub axle, turning the rear wheel. A chain on each side transmits power between the sprockets (similar to a motorcycle). This drive system minimizes the stress on drive-shaft and CV joints and provides a final gear-reduction allowing the use of extra large tires. Four independently inflatable airbags are used instead of leaf or coil-springs and allows adjustment of suspension stiffness and ride-height.

Steering: Howe quick turn power steering rack connected to front wheels thru 2 tie rods. Front wheels are supported by pivoting knuckles with long arm suspension members. Rear axle incorporates minimal roll steer geometry but no active steering.

Brakes: Dual hydraulic ABS system, front and rear vented disc brakes.

Four wheels with pneumatic rubber tires. Rated tire diameter is 39" front, 44" rear. Ground contact area (8x10;10x12) is shown in rectangles. (unit of measure: inches)

2. Autonomous Operations

2.1. *Processing*

2.1.1.

The computational systems on-board the vehicle are divided into several functional blocks, each aligned to a particular system or task, and interconnected via Ethernet in order to send and receive commands and sensory data. The architecture follows a “Sense-Model-Plan-Act” model for autonomous vehicle control, with adaptations to provide for data access and logging across these functional blocks:

System	Purpose	Hardware
PROPULSION (single node)	Dedicated control and supervision of vehicle locomotion, including throttle, shifter, braking and steering. Responds to commands issued by the **DRIVER** node. Monitors feedback from State Sensors and communicates to Driver	. Custom made microprocessor controlled circuit board. Details Proprietary.
SENSOR (multiple nodes, currently specified at two)	Management and data processing for one or more sensor packages (Ladar, GPS, compass, solar tracker, etc.). Includes hardware interface to the sensor(s).	Implemented using Mini-ITX small-footprint PC motherboards, with 1.8GHz Intel M processor running the GNU/Linux operating system. 1 MB SDRAM
SUPERVISOR (single node)	Central node in a star topology for communication, collects, logs and distributes information from multiple sources. Also performs high-level watchdog functions for the system.	Implemented using Mini-ITX small-footprint PC motherboards, with 1.8GHz Intel M processor running the GNU/Linux operating system. 1 MB SDRAM
NAVIGATOR (single node)	Repository for terrain database, including digital elevation maps, vector representations of environment. Pre-loaded with available data, this node also collects and records sensed navigation data. Aligned to the "Plan" functional block, this node performs the macro navigation tasks.	Implemented using Mini-ITX small-footprint PC motherboards, with 1.8GHz Intel M processor running the GNU/Linux operating system. 1 MB SDRAM
DRIVER (single node)	Responsible for sensory fusion and high frequency decision making, this node issues commands to the PROPULSION node. Part of the "Plan" functional block, this node is responsible for the real-time, micro navigation tasks.	Implemented using Mini-ITX small-footprint PC motherboards, with 1.8GHz Intel M processor running the GNU/Linux operating system. 1 MB SDRAM
VISION (single node)	Gathers and processes camera data into digested data products for the **DRIVER** and **NAVIGATOR** nodes, primarily obstacle avoidance, lane following and surface characterization information.	Implemented using Mini-ITX small-footprint PC motherboards, with 2.0GHz Intel M processor running the GNU/Linux operating system. 2 MB SDRAM

All nodes use compact Flash cards for 'hard' memory.

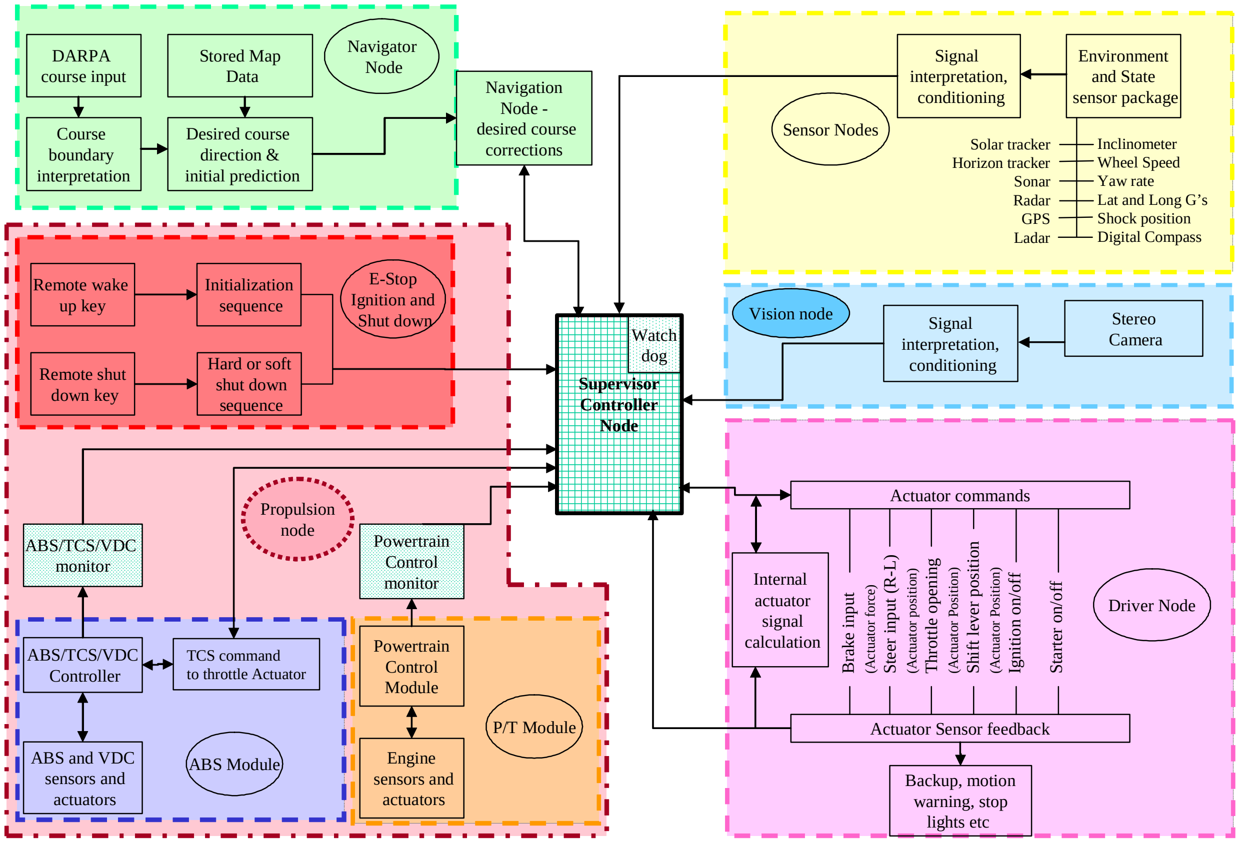
A separately powered independent stand-alone PC board with hardwired logic monitors the ’hard’ E-stop binary signal output and the manual E-stop switches and implements the disable mode (communicating directly with affected actuators) in case of a commanded ‘hard’ E-stop.

Internal Databases:

The on-board terrain database is composed primarily of digital elevation models, typically sourced from USGS. A commercially sourced composite database (from Terrain Navigator and Lowrance) of man-made features such as roadways, railroad tracks, power lines and fence lines, has been digitized to matching format and is used in the path planning. Other layers, such as the hydrological features of the region, are stored for use in calculating navigability or sensor disambiguation. The database will be augmented with layers describing desirable routes across specific terrain that **NAVIGATOR** may use to construct routes during the mission. The terrain database is populated with sensed data during the mission and discrepancies from pre-stored data are managed to optimize route calculations in scenarios such as backtracking.
The software is developed according to well defined formal methods based on the SEI-CMM; with design documents, coding standards, and state and timing charts. The majority of the software is developed in the C programming language, with some assembly language routines as needed for custom hardware initialization. Each processing node will send a heartbeat notice to the SUPERVISOR module, and the SUPERVISOR module will regularly broadcast a heartbeat message to the other processing nodes. In the event of two missed heartbeat messages, the SUPERVISOR node will trigger an e-stop and a soft reboot of the failed processing node. In the event that the SUPERVISOR module fails to issue a heartbeat message, any other processing node can trigger a restart of the SUPERVISOR node. The processing nodes will be protected from power supply failures by an auto-switching dual power supply; other critical subsystems will be monitored by watchdog routines in the processing nodes and can take appropriate actions based on the cause of failure.

2.1.2.

Computational System Block Diagram



2.1.3.

The development process employed by the team was organic growth. First the 'drive-by wire vehicle behavior was characterized using remote control. The 'real-world' characteristics of OTS sensors were learned thru hundreds of hours of tests and recordings. Autonomous operation initially consisted of simple GPS waypoint following. Additional sensors were added and fusion algorithms developed to enable pathfollowing during GPS outages. A sensor was added to detect near obstacles. As confidence level increased with various driving scenarios then additional sensors were added to allow modeling a more complex environment. A model environment with easily predictable behaviors was created to limit the control variables required to execute the tests.

2.2. *Localization*

The localization system employs two GPS units, two IMU units, a sun tracker, and a set of vehicle reference sensors (wheel encoders and steering position encoder) for dead reckoning.

GPS

The CSI Wireless Vector GPS provides heading, latitude, and longitude using WAAS corrections. The CSI Wireless DGPS provides heading, latitude, and longitude using Omnistar corrections.

There are two types of receivers in operation on-board the vehicle.
The first type of receiver is a system of L1 (1575.42 MHz) Global Positioning System receivers utilizing the freely available Standard Positioning Service. Additionally, these receivers will typically make use of the satellite-based augmentation system “WAAS”, which is also freely available. The use of these signals is intended to comply with sections 6.1 and 6.7 of the Grand Challenge Rules (v1.2).

The second type of receiver is for Differential GPS. The vehicle will carry a tunable receiver operating between 283.5 KHz and 325 KHz to receive DGPS corrections broadcast by the United States Coast Guard. As these transmissions are freely available for use, this receiver is intended to comply with sections 6.1 and 6.7 of the Grand Challenge Rules (v1.2). The coverage and effectiveness of the USGS DGPS corrections is uncertain in the region of the course, so the need for additional DGPS resources is anticipated. Pursuant to section 6.7 of the rules, the use of a subscription-based service is requested. This service will be provided by OmniSTAR USA, Inc. and will consist of an L-band satellite receiver. This will receive only DGPS correction information and is compliant with section 6.1 of the rules in that the data received is entirely beyond the control of the team

The accuracy of system performance is directly linked to accuracy of the fusion weights. If a measurement is given greater weight than deserved given its actual variance, then the resulting fusion will be partially and temporarily skewed. However, so long as such errors are random and transient, the effects will be negligable. We have taken great consideration in our prefilter to ensure that all measurements fall within appropriate ranges and that all measurement variances are reflective of device status. We account, for instance, for locations of known magnetic anomalies when determining the usability of our magnetic devices. Failability in one system is compensated by other systems.

Location is collectively given by the two GPS units and the dead reckoning system. Heading is collectively given by the two inertial units, the sun tracking unit, the dead reckoning system, and the two GPS units.

IMU

The CrossBow DMU-VGX and the MicroStrain 3DM-GX1 both provide dynamically-stabilized and temperature-compensated yaw, pitch, and roll measurements using triaxial accelerometers, magnetometers, and rate gyros. Both devices are referenced to gravity and magnetic north. To convert to true north, we add the magnetic declination provided by the International Geomagnetic Reference Field (IGRF) for the current latitude, longitude, and date.

Sun Tracker

The Santa Ana High School Engineering Club designed and built the sun tracker device. The unit consists of a set of five Taosinc TSL-230 light to frequency ICs mounted on a servo head for active tracking and a Parallax BS2P basic stamp for data processing. The device calculates relative azimuth, elevation, and light intensity and outputs this data via RS232 serial. The relative azimuth and elevation are converted to true azimuth and elevation for the current latitude, longitude, and time by data from the United States Naval Observatory.

Vehicle Reference Sensors

The vehicle reference sensors consist of a set of quadrature encoders to measure the rotation rate of the wheels, an LVDT to measure the steering angle, and the feedback from the steering, throttle, transmission, and brake actuators. Collectively, this information is integrated into a model of vehicle dynamics and used for dead reckoning. Two whiskers mounted on the front bumper senses objects in close lateral proximity (i.e. wall of tunnel)

Architecture

The GPS and and IMU connect directly into the Navigation computer. The Vehicle Reference Sensors connect to the SBTT computer, which connects to the Navigation computer by serial port. On the Navigation computer separate processes initialize and maintain connection to each sensor, synchronize, convert, and verify each measurement, and pass the output to the fusion process.

Fusion

The fusion process receives asynchronous measurements from the navigation sensors. It uses these measurements in a predictive corrective model to estimate the translational and rotational position, velocity, and acceleration of the vehicle. Because the system is distributed and redundant, it remains functional - albeit with some degredation of performance - under the temporary or even permanent loss of any individual sensor. Furthermore, because the system is aware of its own performance, it can provide higher level processes with an indication of the severity and nature any failures present to allow for scenario detection and problem solving.

GPS Outage

When all systems are functioning, translational position, velocity, and acceleration are provided by the vehicle reference sensors with drift corrected by the GPS units. In the event of a GPS outage, dead reckoning will continue to provide positional information with increasing drift. Again, specific scenarios are handled at a higher level of processing.

Tunnels for instance, are detected by vision and handled by ladar and whisker probing rather than blind localization.

2.3. *Sensing*

2.3.1.

Ladar; 1 unit mounted 4 ft behind c/l of front wheel, 2ft right of centerline on pan/tilt table approx 7 ft above ground. 1 unit mounted 4 ft behind c/l of front wheels, 2 ft left of Vehicle centerline on tilt fixture approx 6 ft above ground. 1 unit mounted 1 ft in front of of c/l of front wheels approx 2 ft above ground. 1 unit mounted vertically with secondary oscillating mirror approx 3ft behind centerline of vehicle 5 ft above ground.
2 SICK LMS 291-S5. Field of view 110 degrees. Range 100 ft. 2 SICK LMS 291-S5 Field of view 90 degrees. ½ degree resolution. 15,000 pulses per second.
Doppler Radar; mounted 1 ft in front of c/l of front wheel approx 4 ft above ground. Radar unit: Eaton Vorad VBOX 83001-001 Field of view 12 degrees. Range 300 ft. 2 degrees resolution.

Tactile sensors: '2 Catwhiskers' fix mounted, spring loaded, on sides of front bumper extending approx 1 ft to the left and right of front wheels. Proprietary whisker construction includes water level sensor.
Custom assembly of 1 Near-field and 1 far-field Stereo camera: fix-mounted approx 4 ft behind centerline of front wheels approx 6ft high. Performance parameters proprietary.
Sonar array: 2 rear. 40 kHz. Range 1 -15 ft, cone angle 15 degrees.

2.3.2.

The **SUPERVISOR** node establishes the control regime for the entire system based on sensory data and mission phase, and is part of a global data set that any system node may use to establish operating parameters. The **SUPERVISOR** is also tasked with asserting a software E-Stop signal if the system health is degraded below minimums. The **NAVIGATOR** determines goal-based routes subject to problem constraints such as course definitions and a priori knowledge of terrain navigability from databases. These routes are fed to the **DRIVER** and updated based on the most current pose estimate. The **DRIVER** node maintains the local environment model and uses it to calculate locomotion commands based on input from the **NAVIGATOR**. The environment model includes elements describing "threats", further classified as either static or dynamic threats, the latter being a moving object such as another vehicle. Based on sensory inputs and the database, objects (obstacles) in the vehicle path are classified as permanent or temporary. Temporary obstacles are objects that either move or are expected to move in the grid. For example see exhibit A. The **PROPULSION** node receives commands from the **DRIVER** and may decline or modify the command based on safety or performance parameters. See also Discussion under 2.2.1

2.3.3. Internal sensing system:

1 Two axis inclinometer. 20 degrees tilt, 8 bit precision.
2 Rotary wheel-encoders, both front wheels, 9 cm increments.
3 Gyros, .5 – 75 degrees per second. (part of IMU)
2 Linerar position sensor for shifter and steering
3 Accelerometers, .05 – 3g. (part of IMU)
1 Solar tracker, (custom built, 3 degree resolution, 100 Hz).
1 engine tachometer, 0 – 8,000 rpm.
1 cooling water temperature sensor, 120 – 260 degrees F.
1 shifter position sensor, binary 6 outputs.
pressure transducers, brakes.
Certain other sensors are present in self regulating systems (i.e alternator, ignition, gps)

The tachometer is used to verify that the engine is running (start, idle) and prevent the engine from over-revving. The cooling water temperature sensor is used to turn on cooling fan when needed and limit throttle position at excessive temperatures. The shifter position sensor generates feedback during shifting and stops the actuator in the desired position.. One linear motion sensor generates feedback on the steering rack position. A pressure transducers generate feedback from the brake lines.

One gyro determines yaw rate and in combination with the front wheel speed sensors are used to correct steering maneuvers as well as for odometric localization in areas of poor gps reception.. The tilt measurements are also used to determine the vehicle's risk for a roll-over. Two gyros are used to measure rate of change in vehicle tilt during pitch and roll, inputs also used for sensor readout compenstation. The 2 accelerometers are used to measure vehicle acceleration and braking as well as compensating input to the inclinometer readings.

2.3.4.

Following a "Sense-Model-Plan-Act" cycle, sensor data is gathered by **SENSOR** nodes and digested and/or filtered into a data product for communication to the **SUPERVISOR** node. This data is supplied to Model nodes (**DRIVER** and **NAVIGATOR**) for time-offset correction and integration into a pose estimate and environment model. The environmental model is based on a discrete occupancy grid, each grid step being .000003 nautical degrees or approx 30 cm.. As the sensors scan the surrounding terrain, particularly in the direction of the planned path, the grid values are adjusted.. Progressive scans yield information of the (vertical) size of the threat. The radar complements the Ladar by giving information about larger objects further away, plus moving objects in a wider field of view. Likewise, the sonar sensors and the tactile sensors yield information of objects close by for slow, precise speed navigation. The stereo camera helps further define objects in case of need. A drivable (safe) path is calculated based on examining each initial path grid points (imported from the navigator) location to a potential threat, and modifying the initial path for fastest travel (optimizing distance with path curvature. Here the size of the vehicle is also taken into account, and its dynamic steering capabilities. Max speeds defined in the course are taken into account.

Much of the information stored by the navigation algorithm is kept on map layers. Map layers are north-south aligned grids that are maintained approximately centered about the vehicle. As the vehicle traverses the world, this map is maintained by discarding the rows and columns behind the vehicle and replacing them with new rows and columns in front of the vehicle. For example, when ladar information is received by the algorithm, it is loaded into a map layer dedicated to that information. Each of the ladar return values will be mapped onto the appropriate grid cell. As the vehicle moves, subsequent ladar scans are combined with the information already on the map. When provided with a candidate vehicle location, this algorithm will poll the appropriate grid cells and combine them to return the score for that location. Far reaching sensors such as the radar and the far-field stereo camera is instrumental in determining max safe speed. If the actual speed is higher than the desired speed desired deacceleration is determined and achieved either by decremented the throttle only or decrementing the throttle and applying a predefined brakepressure, In turning the width of the vehicle is taken into account for obstacle avoidane.

2.4. *Vehicle Control*

2.4.1.

Missed waypoint: If the vehicle cannot reach a waypoint based on the road picked (the road is blocked or the path takes it outside the boundary) it will stop, reverse and return to the previous waypoint and make a new attempt. The location where it stopped will be given a high traversability score.
Vehicle stuck: If the wheelencoders do not indicate forward movement at a certain throttle/rpm setting. The vehicle will reverse. The location where it stopped will be given a high traversabilty score.
Obstacle in path: See path planner 2.4.3

2.4.2.

Areas outside the route boundary are given a high traversability cost (see 2.4.3)
The path planner takes into consideration the vehicle's maneuverability at various speeds and makes sure the planned path trajectory is within the route boundary. The vehicle's braking capability has been characterized so that a safe speed is always attained and braking started at the appropriate point in time. Starting and stopping on a Hill (incline) has been tested separately. When starting on a hill brakes are applied and gradually released while wheelencoder information is used to ensure the vehicle is not rolling backwards. An integrator gradually increases engine rpm until desired speed has been reached. Sharp turns are always done at reduced speeds.

2.4.3.

The navigation algorithm utilizes information from many different sources. These sources include the RDDF waypoint file, ladar sensors, stereo-vision algorithm, mono-vision algorithm, and radar. When provided with a candidate vehicle location, the "sub-algorithm" associated with each source is responsible for providing the cost for traversing that location based on the information that has been obtained from that sensor. The navigation algorithm computes the cost of a candidate location by combining the scores from all of these multiple sources. The cost of an entire candidate trajectory is the sum of the scores from each point along that trajectory.

The navigation algorithm used on the vehicle is based on a minimum cost model. The algorithm will consider a group of candidate trajectories and choose the one that has the lowest cost. This trajectory is communicated to the driver node of the vehicle with the process now repeating starting at a point further along the trajectory.

Candidate trajectories are chosen based on the vehicle's current state and physical limitations and other factors. The vehicle's state includes its position, velocity, heading, and turn rate. Physical limitations include limits on turning rate and limits on the rate of change of turn rate. The set of possible trajectories is further reduced by removing those candidates that are too similar to another trajectory based on our grid size.

2.4.4.

The vehicle is controlled via two methods when not in autonomous control. The vehicle can be controlled by a team member sitting in the vehicle and "driving by wire" and the vehicle can be controlled via a remote steering and braking system connected to the vehicle via a wireless access point.

Sufficient room has been allocated in the cockpit of the vehicle to accommodate a single driver. Once the driver is in position there are numerous controls for the vehicle. There is a control box for the transmission. Steering and throttle are adjusted using radial knobs on the control panel. Brakes are applied manually by the driver.

The vehicle is also equipment with remote control functionality for use during testing. This functionality is disabled for NQE and the race. During testing periods a wireless access link is establish between the command post and the vehicle. A localized Ethernet LAN on the vehicle is linked via wireless link and a controller laptop in the command post. The controller laptop has a game controller steering wheel and brake/accelerator pedals connect via USB ports. Transmission commands are issued via the driver laptop in the command post.

2.5. *System Tests*

2.5.1. Test Strategy

The test strategy employed by the team was to explore the desert area in the South West USA, record vision and ladar images from that area, find a secluded area near the teams home base where similar environments could be emulated, establish basic vehicle control, build upon that base path following, and then add obstacle avoidance with road identification.

The tests have been designed in a progressive sequence validating simple path following before advancing to more complex navigation routes. Routes were incorporated into the testing that simulated the routes that may be found on the Grand Challenge Course.

A reliability test protocol was established to ensure that the instrumentation would withstand the environment and function reliably for at least 20 hours of continuous operation. Team CyberRider has fieldtested its vehicle for approx 8 hours per week every Saturday since January 2005.

A list of obstacles was identified and simulated on the test course. The test included a determination of reaction times required and clearance from obstacles that should be maintained to insure continuous navigation while circumventing obstacles.

Test results and Key Challenges discovered.

The vehicle can traverse virtually any desert terrain including loose silt, sand, mud, negotiate 12” size rocks, ruts, wash-outs, offering a smooth ride at speeds of 15 – 20 mph, (where ‘regular 4wd vehicle may reach speeds of 5 –10 mph)

The desert heat (up to 110 degrees) did not adversely affect system components including the computational modules.

Key challenges include greater than advertised inaccuracy of the DGPS systems, unpredictable behavior of the SICK units requiring re-boots, shadows and direct sunlight impairing the Stereo cameras, synchronization of sensor information, and various component latencies